

Teaching Magnetic Design using CAD tools

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Abstract. Design of magnetic components is a multivariable problem. There are many different combinations of shapes, sizes and materials for the core with many diameters for the wires. So it is difficult to find the optimum design without a great number of iterations. Analytically only a few combinations are usually studied but it is very easy to take into account all the combinations using a CAD tool [1]. In this work the CAD tool used is PExprt (ANSYS [2]) which is being developed at UPM-CEI.

I. ANALYTICAL DESIGN

Design of magnetic components for power converter is based on the specifications of the power converter (input voltage and current waveforms).

A. Inductors analytical design

To design the inductor it is necessary to select both the core and the conductors. The core is characterized by the size, the shape and the material. The size is commonly selected in order to manage the specified power. The shape depends on the specific application of the component. The material is selected in terms of the switching frequency of the converter. The type of conductor (solid wire or Litz wire) is function of this frequency too. The conductor area implies a limit on the losses and is commonly selected considering the skin effect. The number of turns, N , is selected in order to avoid core saturation (1).

$$N = \frac{L \cdot i_{mx}}{A_e \cdot B_{mx}} \quad (1)$$

With L and N it is possible to calculate the total reluctance of the component, which determines the gap dimensions, if it is necessary.

Once the design is obtained the next step is the losses calculation:

- Core losses are well evaluated with vendor databooks or with the classical Steinmetz model. This model appears in equation (2).

$$P = V_e \cdot k \cdot f^\alpha \cdot \left(\frac{\Delta B}{2} \right)^\beta \quad (2)$$

Where k , α and β are properties that depends on the core material and the frequency and V_e is the effective volume of the core. The goal of the design is to find the magnetic component with least losses, so it is not necessary a very accurate result because the comparative analysis of different designs is more important. A trade-off between precision and efficiency

is needed, so the Steinmetz model is considered the best.

- **Wire losses** have two components Direct Current (DC) losses and Alternating Current (AC) losses. The AC wire losses are produced by the mechanisms of skin effect and proximity effect. Analytically, wire losses are usually evaluated with the following equation:

$$P \propto R_{DC} \cdot I_{eff}^2$$

$$R_{DC} = \rho \cdot \frac{l}{s} \quad (3)$$

Where only DC resistance (RDC) is considered but not AC resistance. This is not very recommendable if the ripple of the current waveform is important compared with the DC level (then AC resistance is not negligible).

If the losses value is right the process is finished, otherwise a new design must be recalculated (iterative process). It is not effective to do a lot of iterations and so it is difficult to obtain the optimum component.

B. Transformers analytical design

In a transformer the combinations are multiplied by the windings number. The initial specifications of the converter define the value of turns ratio. In a transformer the rules to select the core and to select the conductor type are the same as in the inductor. But the conductor area is selected to optimize the losses. Usually the different wires of the windings have the same current density. The following step is to obtain the number of turns of primary side which maintain the core losses bellow a fixed value.

Losses calculation is equal than for the inductor. If the core losses and the wire losses are right the design is finished, otherwise it will necessary to redesign the component. However, not always the optimum design is to reach the same core losses and wire losses, it depends on the kind of core material.

II. CAD DESIGN

The use of the software tool makes possible a better optimization of the components by analyzing a lot of combinations of wires, bobbins and cores possibilities. This would take a lot of time in an analytical way.

A. Inductor and Transformer Losses

- **Core losses.** Steinmetz model continue being the best in the trade-off between efficiency and accuracy.
- **Wire losses.** Both DC losses and AC losses are considered. The expression for the losses is:

$$P = \sum_w R_w \cdot I_w^2$$

Where R_w and I_w are the resistance and current for the w -th harmonic. So, it is necessary an harmonic decomposition of the current waveform and to know the dependence of the resistance with frequency.

Another way to calculate wire losses is with Dowel model, which allows splitting up the losses due to skin effect and the losses due to proximity effect.

It also takes into account the fringing flux, caused by the effect of the gap [3-4], which modifies the window energy. This means a different gap length too.

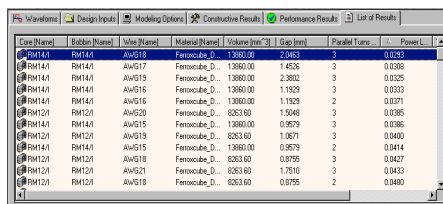
Especially significant is the losses optimization. In an analytical way the optimization can be done referred to the flux density (if the current ripple is big) or to the number of turns (if the current is mainly DC). The frontier between two limits is not clear. As a solution the CAD tool optimize both of them, starting with the design with the minimum number of turns and increasing it discreetly, it finds a minimum in the losses.

B. CAD Design versus Analytical Design

- CAD design is more flexible than analytical design and it is not necessary to be an expert designer.
- Design of magnetic components is a multivariable problem and the optimization is not easy. However, using a CAD tool it is very easy to take into account all the combinations.
- Analytical equations of magnetic components are difficult to solve, but it is easy to implement these equations in a software tool.
- The main drawback is that it is necessary to buy and to learn how to use the different CAD tools.

PExpert specific advantages

- It has a friendly interface.
- It prevents construction problems, by selecting only the stock components.
- The output of the analysis is a list of components (Figure 1.), so the designer can compare different designs and choose the better using his/her own guidelines (less power losses, volume, height, footprint, temperature...).



| Core Name | Winding Name | Wire Name | Material Name | Volume [mm³] | Gap [mm] | Parallel Turns | Power L. |
|-----------|--------------|-----------|-----------------|--------------|----------|----------------|----------|
| RM121 | RM121 | AWG18 | Ferroxcube_D... | 12000.00 | 2.000 | 3 | 0.003 |
| RM141 | RM141 | AWG17 | Ferroxcube_D... | 14000.00 | 1.400 | 3 | 0.010 |
| RM141 | RM141 | AWG19 | Ferroxcube_D... | 13000.00 | 2.300 | 3 | 0.025 |
| RM141 | RM141 | AWG16 | Ferroxcube_D... | 13000.00 | 1.100 | 3 | 0.033 |
| RM141 | RM141 | AWG16 | Ferroxcube_D... | 13000.00 | 1.100 | 2 | 0.071 |
| RM121 | RM121 | AWG20 | Ferroxcube_D... | 6263.60 | 1.500 | 3 | 0.085 |
| RM141 | RM141 | AWG15 | Ferroxcube_D... | 13000.00 | 0.900 | 3 | 0.086 |
| RM121 | RM121 | AWG19 | Ferroxcube_D... | 6263.60 | 1.000 | 3 | 0.080 |
| RM141 | RM141 | AWG15 | Ferroxcube_D... | 13000.00 | 0.900 | 2 | 0.014 |
| RM121 | RM121 | AWG18 | Ferroxcube_D... | 6263.60 | 0.800 | 3 | 0.047 |
| RM121 | RM121 | AWG21 | Ferroxcube_D... | 6263.60 | 1.700 | 3 | 0.043 |
| RM121 | RM121 | AWG18 | Ferroxcube_D... | 6263.60 | 0.800 | 2 | 0.040 |

Figure 1. List of results of PExpert.

- It allows a quick documentation, because of the easy generation of text files and screen captures.

- It also allows an automatic model generation of the magnetic component. The model can be 1D analytical, based in transmission lines for PSpice and Simplorer simulators. It is also possible to obtain a 2D/3D model, based in Finite Element Analysis Tools (FEA). It is very useful to have a model to study the component not only as an isolated component but also as a part of a power converter.

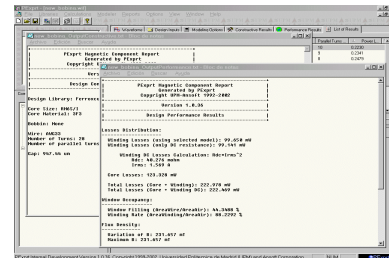


Figure 2. PExpert Text Files for documentation.

C. Design Steps

Next, the design steps of magnetic components with PExpert are described (grouped by sections).

Specifications

There are two ways to input the initial specifications of the power converter, which are shown on Figure 3. The first one is using the current and voltage waveforms and the second one with the specific topology of the power converter.

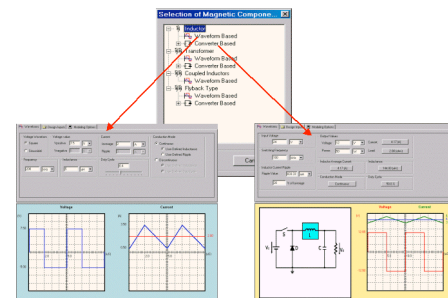


Figure 3. Diagram of PExpert Input Specifications

If the input is based on the waveforms, there is not any restriction in the type of inductor or transformer that can be designed.

If the input is based on the converter specification, the available are:

- Inductor of a Buck.
- Inductor of a Boost.
- Inductor of a Buck-Boost.
- Transformer of a Classic Forward.
- Transformer of a Half Bridge.
- Transformer of a Full Bridge.
- Transformer of a Half-Bridge.
- Transformer of a Push Pull.
- Transformer of a Flyback.

Constructive Results

For example:

- Wire type.
- Number of turns.
- Gap length.
- Core size and material.

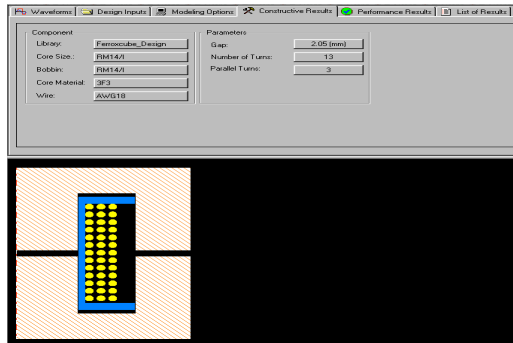


Figure 7. Constructive Results

Performance Results

For example:

- Losses.
- Window occupancy.
- Flux density.

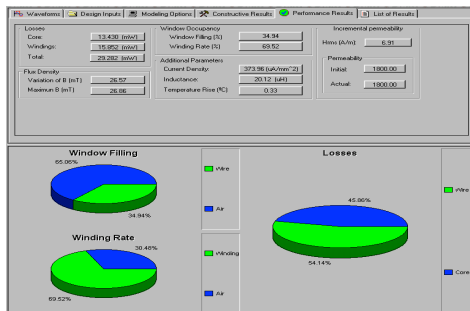


Figure 8. Performance Result

Modeling

There is a link with the Maxwell FEA tool, for a 2D/3D modeling of magnetic components.

There is also another one for building a 1D analytical model based in transmission lines to study the global converter. The model can be implemented in an electrical simulator, like PSpice or Simplorer.

III. EXAMPLE. TRANSFORMER OF A FLYBACK.

A. Specifications

The main converter specifications are shown in the following table. The circuit is shown in Figure 9. The transformer is working in Continuous Conduction Mode.

| | |
|---------------------|---------|
| Input Voltage | 48 V |
| Output Voltage | 50 V |
| Power output | 100 W |
| Switching Frequency | 100 kHz |
| Maximum Current | 0.458 A |
| Current Ripple | 1.66 A |
| Inductance | 150 mH |
| Duty Cycle | 50% |

Table 1. Converter Specifications

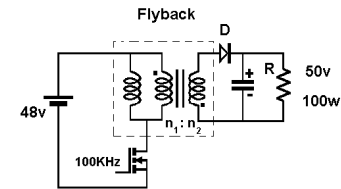


Figure 9. Flyback topology

B. Analytical Design

The Analytical design of the inductor has been obtained in the way described in previous sections:

| | Design A.1 | Design A.2 |
|--------------------------|------------|------------|
| Core Size | RM12/I | RM12/I |
| Core Material | 3F3 | 3F3 |
| Primary | | |
| Irms | 2.83 A | 2.83 A |
| Wire Diameter | 0.4 mm | 0.4 mm |
| Number of Turns | 27 | 27 |
| Number of Parallel Turns | 3 | 5 |
| Secundario | | |
| Irms | 2.95 A | 2.95 A |
| Wire Diameter | 0.4 mm | 0.4 mm |
| Number of Turns | 27 | 27 |
| Number of Parallel Turns | 3 | 5 |
| Gap | 855 mm | 855 mm |
| Windings Losses | 1.24 W | 744 mW |
| Core Losses | 37 mW | 37 mW |
| Total Losses | 1.51 mW | 781 mW |

Table 2. Results of the analytical designs

Designing is an iterative process. As the winding losses were very high in Design A.1, a new design of less losses (Design A.2) is obtained with more parallel conductors in both primary and secondary side of the transformer.

C. PExprt Design

PExprt data input is based on the converter specifications. The input voltage and current waveforms on the transformer extracted from the tool are shown in Figure 10. and Figure 11.

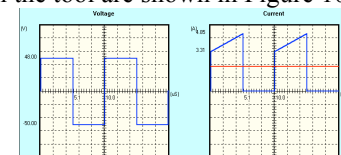


Figure 10. Voltage and Current waveforms on the primary side

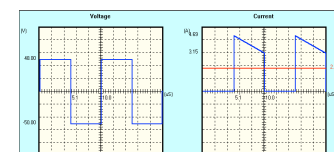


Figure 11. Voltage and Current waveforms on the secondary side

Searching for the Analytical Design with PExprt

Among the numerous solutions that are calculated with PExprt, one of them (Design B) is equal to the analytical design (Design A.2):

| | |
|--------------------------|-------------------|
| Core Size | RM12/I |
| Core Material | 3F3 |
| Primary | |
| Irms | 2.9 A |
| Wire Diameter | AWG27 0.4 mm |
| Number of Turns | 27 |
| Number of Parallel Turns | 5 |
| Secondary | |
| Irms | 2.8 A |
| Wire Diameter | AWG27 0.4 mm |
| Number of Turns | 27 |
| Number of Parallel Turns | 5 |
| GAP | 873.8 mm |
| Window Filling Factor | 48.8 % |
| Windings DC Losses | 836.523 mW |
| Windings AC Losses | 881.1 mW |
| Core Losses | 35.1 mW |
| Total DC Losses | 871.6 mW |
| Total AC Losses | 916.2 mW |
| Temperature Rise | 16 °C |

Table 3. Design B

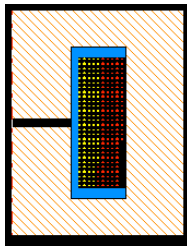


Figure 12. Axial View of the Design B

The losses results are very similar. There are only little differences with the winding losses because of the effective currents, which are not exactly the same for both designs.

Using the wire diameter as degree of freedom and keeping the core constant.

The core is kept constant and all wires of the stock library are selected. PExprt design of fewer losses is the previous one. The harmonic content of the current waveform is very high, so the wire selected analytically is the best. Skin effect must be considered for the wire selection.

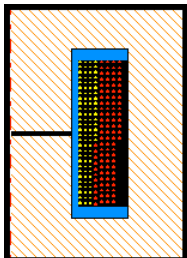


Figure 13. Axial View of the Design C

Changing the core type

If the core selected is smaller, there is not a design of fewer losses than the Design B.

If the core selected is bigger (RM14/I), the losses decrease:

| | |
|--------------------------|-----------------|
| Core Size | RM14/I |
| Core Material | 3F3 |
| Primary | |
| Irms | 2.9 A |
| Wire Diameter | AWG25 (0.51 mm) |
| Number of Turns | 20 |
| Number of Parallel Turns | 5 |
| Secondary | |
| Irms | 2.8 A |
| Wire Diameter | AWG24 (0.57 mm) |
| Number of Turns | 20 |
| Number of Parallel Turns | 5 |
| GAP | 633.4 mm |
| Window Filling Factor | 42.5 % |
| Windings DC Losses | 405.9 mW |
| Windings AC Losses | 444.7 mW |
| Core Losses | 58.2 mW |
| Total DC Losses | 464.1 mW |
| Total AC Losses | 502.9 mW |
| Temperature Rise | 6.3 °C |

Table 4. Design C

It is interesting to increase a bit the size of the transformer because the Window Filling Factor of Design B is very high and it can be difficult to build. With this new design, Design C, winding losses fall and core losses are still low, so it is a very good design.

Gap effect

In this section, the purpose is to emphasize the utility of use 2D/3D FEA models to design magnetic components. With these models it is possible to study the gap effect in the losses of the magnetic component.

The way to use a FEA model is with PExprt Analysis Mode. Previously, a PExprt FEA model must be extracted from the appropriate link. It is easier to implement these models in a CAD tool versus its use in the analytical design.

The design selected is Design B. It has not a very big gap but as it is a design with a lot of turns, the gap effect becomes very important, so accurate winding losses can be calculated with this model:

| | |
|--------------------------|----------------|
| Core Size | RM12/I |
| Core Material | 3F3 |
| Primary | |
| Irms | 2.9 A |
| Wire Diameter | AWG27(0.4 mm) |
| Number of Turns | 27 |
| Number of Parallel Turns | 5 |
| Secondary | |
| Irms | 2.8 A |
| Wire Diameter | AWG27 (0.4 mm) |
| Number of Turns | 27 |
| Number of Parallel Turns | 5 |
| GAP | 873.8 mm |
| Window Filling Factor | 48.9 % |
| Windings DC Losses | 836.5 mW |
| Windings AC Losses | 25.3 W |
| Core Losses | 43.1 mW |
| Total DC Losses | 879.2 mW |
| Total AC Losses | 25.4 W |
| Temperature Rise | 442.2 °C |

Table 5. Design C modified

AC losses have a great increase compared with the Dowell

model losses [5]. This can induce errors when less losses design is being selected, and this is illustrated with the following example.

In Figure 14., there is a list of results calculated with Dowell model sorted by losses.

| Core (Name) | Wire (Name) | Volume (mm ³) | Turns | Temperature | Gap (mm) | Parallel Turns | Power L |
|-------------|-------------|---------------------------|-------|-------------|----------|----------------|---------|
| RM14/I | AWG22 | 13660.00 | 20 | 10.49 | 0.6334 | 2 | 0.9977 |
| RM14/I | AWG27 | 13660.00 | 20 | 10.93 | 0.6334 | 5 | 0.9012 |
| RM14/I | AWG26 | 13660.00 | 20 | 10.51 | 0.6334 | 4 | 0.9016 |
| RM14/I | AWG27 | 13660.00 | 20 | 10.76 | 0.6334 | 4 | 0.9016 |
| RM14/I | AWG28 | 13660.00 | 20 | 11.08 | 0.6334 | 5 | 0.9019 |
| RM14/I | AWG25 | 13660.00 | 20 | 10.73 | 0.6334 | 3 | 0.9120 |
| RM14/I | AWG20 | 13660.00 | 20 | 10.71 | 0.6334 | 1 | 0.9149 |
| RM14/I | AWG22 | 13660.00 | 20 | 10.63 | 0.6334 | 2 | 0.9152 |
| RM14/I | AWG22 | 13660.00 | 20 | 10.62 | 0.6334 | 2 | 0.9155 |
| RM14/I | AWG16 | 13660.00 | 20 | 10.85 | 0.6334 | 1 | 0.9182 |
| RM14/I | AWG19 | 13660.00 | 20 | 10.77 | 0.6334 | 1 | 0.9199 |
| RM14/I | AWG20 | 13660.00 | 20 | 10.97 | 0.6334 | 1 | 0.9213 |

Figure 14. List of results.

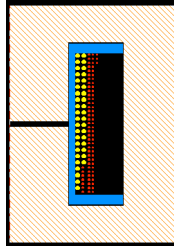


Figure 15. Axial View of the Design D

Two designs are compared; the Design B (in blue) and the following design in losses, named Design D (in red). Design D has more losses than Design B, but the gap of Design D is smaller. As the gap effect increases the losses, this influence will be less considerable in Design D. This can be observed in the following table:

| | Dowell model | PExprt model |
|--------------------------|--------------------|--------------------|
| Core Size | RM14/I | RM14/I |
| Core Material | 3F3 | 3F3 |
| Primary | | |
| Irms | 2.9 A | 2.9 A |
| Wire Diameter | AWG23 (0.64mm) | AWG23 (0.64mm) |
| Number of Turns | 20 | 20 |
| Number of Parallel Turns | 2 | 2 |
| Secondary | | |
| Irms | 2.8 A | 2.8 A |
| Wire Diameter | AWG27 (0.41 mm) | AWG27 (0.41 mm) |
| Number of Turns | 20 | 20 |
| Number of Parallel Turns | 4 | 4 |
| GAP | 633.4 mm | 633.4 mm |
| Window Filling Factor | 21.7 % | 21.7 % |
| Windings DC Losses | 785.2 mW | 785.3 mW |
| Windings AC Losses | 858.5 mW | 12.9 W |
| Core Losses | 58.2 mW | 67.8 mW |
| Total DC Losses | 843.5 mW | 853.1 mW |
| Total AC Losses | 916.7 mW | 13 W |
| Temperature Rise | 10.8 °C | 154 °C |

Table 6. Design D

PExprt losses of Design D are smaller than the ones of Design B. If the effect of the gap in the losses is taken into account, the position of both designs will exchange the order in the list of results.

Finally, PExprt losses of Design C have been calculated in order to study if this design is still the optimum design:

| | |
|--------------------------|-----------------|
| Core Size | RM14/I |
| Core Material | 3F3 |
| Primary | |
| Irms | 2.937 A |
| Wire Diameter | AWG25 (0.51 mm) |
| Number of Turns | 20 |
| Number of Parallel Turns | 5 |
| Secondary | |
| Irms | 2.878 A |
| Wire Diameter | AWG24 (0.57 mm) |
| Number of Turns | 20 |
| Number of Parallel Turns | 5 |
| GAP | 633.4 mm |
| Window Filling Factor | 42.5 % |
| Windings DC Losses | 405.9 mW |
| Windings AC Losses | 14.3 W |
| Core Losses | 67.8 mW |
| Total DC Losses | 473.7 mW |
| Total AC Losses | 14.4 W |
| Temperature Rise | 180.8 °C |

Table 7. Final design

Design D presents fewer losses than Design C, because the first one has less number of turns. The optimum design (of less losses) has changes when a PExprt model is used.

IV. CONCLUSIONS

As the current ripple is important, skin effect must be considered for the wire selection. That is why the wire selected analytically is the PExprt optimum too.

Other way to compute AC wire losses is the use of 2D/3D FEA models and, so 2D/3D effects can be taken into account, for example, gap effect. If the gap effect is important, as in this example, these models are very useful: there are changes in the design positions in the list of results ordered by losses. It is easier to implement these models in a CAD tool versus its use in the analytical.

This example has illustrated the advantages of using magnetic design CAD tools in order to teach particular effects. The combination of slides, blackboard and CAD tools are an excellent receipt for explaining magnetic design.

V. REFERENCES

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